NASA-CR-200806

FORMATION OF THE SOLAR HELIUM SPECTRUM

NASA Grant NAGW-3603

Final Report

For the period 1 June 1993 through 31 May 1996

Principal Investigator

Eugene H. Avrett

April 1996

Prepared for

National Aeronautics and Space Administration

Washington, D.C. 20546

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The NASA Technical Officer for this Grant is Dr. William J. Wagner, Code SSS, Headquarters, National Aeronautics and Space Administration, Washington, DC 20546.

Final Report

Grant: NAGW-3603

Title: Formation of the Solar Helium Spectrum

PI: Dr. Eugene H. Avrett

Co-I: Dr. Dimitar D. Sasselov

In completing our project we have achieved a modern comprehensive understanding of the formation of the solar helium spectrum. Our study brought about the new concept of the one-dimensional complexity in the contribution function of subordinate helium transitions, and a quantitative confirmation of interspecies effects. This opens possibilities for many future applications.

1. Background

Spectral lines of both He I and He II are present in the spectrum of the Sun, arising in its upper chromosphere and transition region. However, their exact mechanism(s) of formation is still a controversial issue and calculated profiles, even for the quiet Sun models, fit the observations poorly. This is especially true for one of the most commonly observed lines, He I λ 10830 , and for He II λ 1640 . Different ideas have been proposed for the mechanism of excitation, and the controversy has centered on collisional vs. radiative excitation and ionization. The theoretical complications have been compounded by the lack of calibrated high spectral and spatial resolution data of the lines, almost all of which are in the EUV and UV. Important He II lines like He II λ 304 and He II λ 256 had no observed resolved calibrated profiles until recently (Thomas, Neupert, & Thompson 1991). Different mechanisms have been shown to play a role in the formation of the solar helium spectrum, but their relative importance in general, as well as in different solar regions, is not established yet and leads to the mentioned discrepancies. We set out to solve thse problems by taking advantage of significantly improved theoretical tools and atomic data, combined with high quality UV spectroscopy.

2. The Helium Spectrum

2.1 The Subordinate He Lines

Both H and He II are major constituents of the upper solar atmosphere and affect each other. The hydrogenic structure of the excitation states of He II invites for radiative effects between H and He II. We treated them simultaneously and consistently in order to quantify such effects on the populations of the subordinate He II lines.

A unique observational opportunity to study these non-LTE effects is offered by the ultraviolet spectral solar atlas obtained by the High-Resolution Telescope and Spectrograph (HRTS), flown on rockets as well as Skylab 2. The HRTS spectrograms combine high spectral (0.05 Å) and spatial ($\leq$ 1 arcsec) resolution, and cover the range 1185–1730 Å. There are about 1000 spatially resolved data points along the length of the slit. The spectra contain simultaneously recorded calibrated profiles of H I Lyα and He II λ 1640 . During the first year of our project we acquired the entire relevant part of the HRTS database. It consists of all positions along the slit for two wide spectral windows centered on the He II λ 1640 line and the H Lyα line, four exposures each. The data was kindly supplied by Dr. Paal

Brekke (Institute of Theoretical Astrophysics, Oslo), and is currently on disk on our workstation at CfA.

The use of all spectral cuts (about 1000) along the slit, as required by our project, brought about the need for extensive data reduction. In particular, to cover the large dynamic range in the intensity of the emission lines, one has to use all exposures and splice together the different profiles for each cut. Due to the large amount of data involved (all cuts along the slit), the splicing has to be done automatically; until now it had been done interactively (Brekke 1992, Wahlstrom 1992). With the kind help of Paal Brekke, who visited us at CfA, all H Ly α spectra were spliced.

The He II λ 1640 line is central to our project, yet it is a blend with the 1640.15Å Fe II $a^4F \rightarrow y^4G^0$ transition (ΔJ = 3/2$\rightarrow$5/2). The HRTS spectra provide a unique opportunity to correct accurately for the Fe II line blending with the He II line, because two other Fe II lines arising from the same upper level, a^4F, are recorded simultaneously in the near vicinity. These are Fe II $a^4F \rightarrow x^4D^0$ transitions at 1637.4Å (ΔJ = 9/2$\rightarrow$7/2) and 1643.6Å (ΔJ = 7/2$\rightarrow$5/2), respectively. All spectral lines in question are illustrated in Figure 1.

In order to develop a successful automatic routine to remove the Fe II blend from all 1000 spectral cuts, one of us (D.D.S.) visited the University of Oslo to work with Prof. M. Carlsson and Dr. P. Brekke in August 1994. With the expertise and software developed during this visit, we also reduced other spectral lines along the slit of the HRTS spectrum, *e.g.* C IV, O III, and compare them to He II λ 1640 .

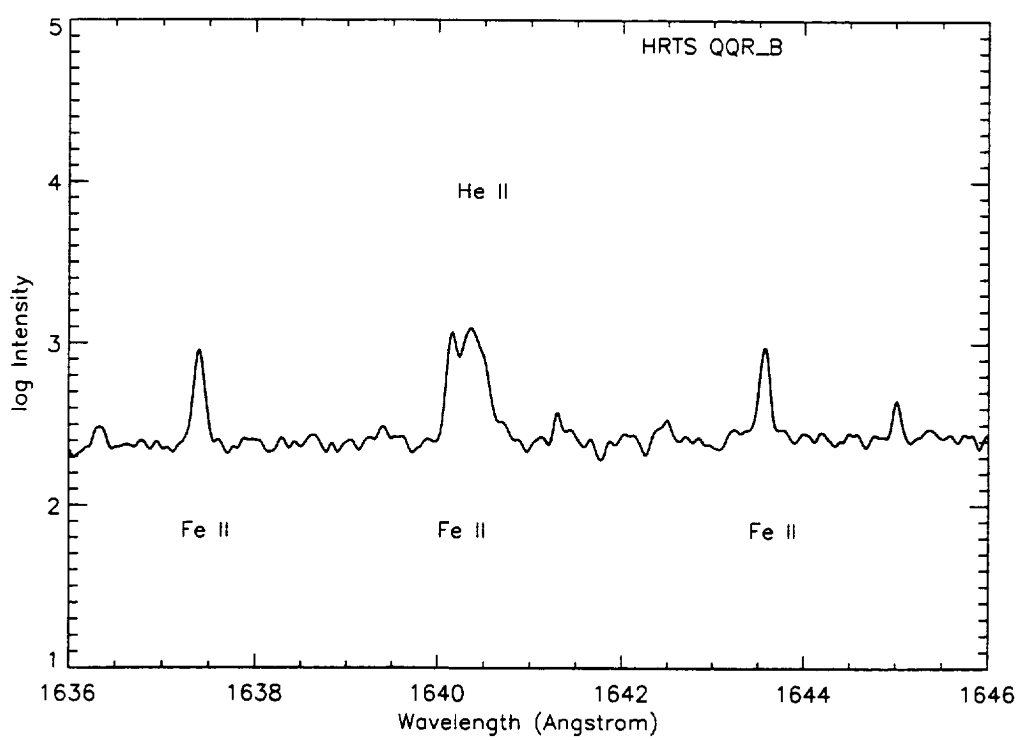

Figure 1: A segment of the solar spectrum centered on the He II λ 1640 line in a quiet region 2/3 of the way to the limb.

Our study of the Fe II blend of He II λ 1640 offered some surprising results. We found that both the flux and velocity of the two x^4D^0 Fe II lines vary in different quiet solar regions and among themselves. The ratio of their intensities may vary as much as a factor of 1.5 and over several raster lines, hence may not be explained by noise. The same applies to their wavelength shifts. Therefore the assumption of common formation conditions for the two x^4D^0 Fe II lines is not good. This places a limit on the accuracy with which the He II λ 1640 line profile can be recovered from the Fe II blend, and enforces the need to perform the subtraction separately for each individual location on the solar disk.

We performed detailed multi-level non-LTE computations in the one dimensional quiet Sun models of Fontenla, Avrett, & Loeser (1993). These models have a detailed treatment of particle diffusion, including the resulting departures from local ionization equilibrium and the transport of ionization energy. For the incident radiation we use the observed solar irradiances in the extreme ultraviolet compiled by Tobiska (1991). The profile of H I Lyα is calculated using partial frequency redistribution (PRD) of line photons and its frequency-dependent radiation field is input in the He solution. The multi-level atomic models of H, He I, and He II are all solved simultaneously. The fine-structure levels are included and all transitions are solved in detail.

The theoretical results on the He I λ 10830 and He II λ 1640 lines are illustrated in Figures 2 and 3, respectively, in terms of their contribution functions (CFs). The CFs for both transitions exhibit the same complex structure in height. The "tail" seen in both CFs results from the increased transition number densities due to photoionization by the incident coronal radiation. The process is aided by a stronger photoionizing flux (see Fig.3 of Avrett, Fontenla,& Loeser 1992), but the effect on the number densities saturates very soon. What controls the overall strength of the emerging line profile is then the integrated optical depth of the transition. This would vary between He I λ 10830 and He II λ 1640 even when the coronal irradiation is the same, because of the local (on the disk) conditions.

2.2 The Resonance He II Lines

Aside from being the most important and the strongest emission lines in the solar EUV region, the resonance lines of He II play an important role for the He I spectrum through helium ionization in the chromosphere. For a range of conditions, sufficient flux from the wings of the He II λ 304 line can penetrate into the upper chromosphere, ionize He I, and affect the strength of, *e.g.* the He I λ 10830 line (Sasselov & Lester 1994).

Therefore we paid special attention to our atomic model of He II, the profile calculation for He II λ 304 , and the effect on the subordinate lines, as illustrated in the previous section. As a result of our proposal Kisielius, Berrington, & Norrington (1996) calculated collision strengths for the fine-structure transitions of $n = 1, 2, 3, 4$ in He II. Such rates for $n = 3, 4$ in He II are now available for the first time. The fine-structure calculations revealed that autoionizing resonances enhance the collision strength by up to a factor of 3 over previous estimates for excitation of the $n = 4$ levels.

3. Summary

Our project attained its goal of developing a detailed consistent treatment of H, He I, and He II under the most common conditions in the solar atmosphere. In addition to employing all relevant physics, our approach makes use of the most complete and current compilation of atomic data available, including rates computed especially for our project. Our models would be a useful interpretive tool for the most recent solar missions of NASA.

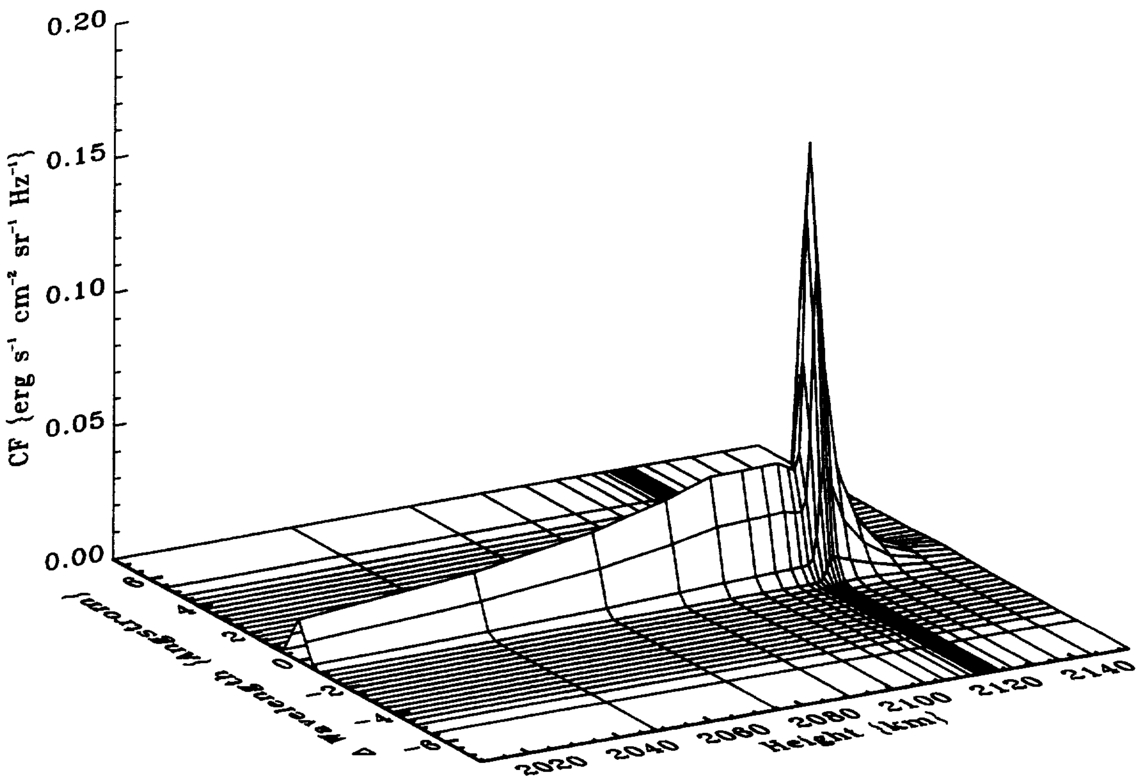

Figure 2: The contribution function of the He I λ 10830 transition, which illustrates the formation regions of the emergent absorption line in the solar spectrum. The calculation was performed with the FAL Cm solar model. The He I λ 10830 line is formed over a range of conditions in the upper solar chromosphere, where coronal photoionization contributes to an overpopulation of the 2^3S level, and in the lower transition region by collisional excitation.

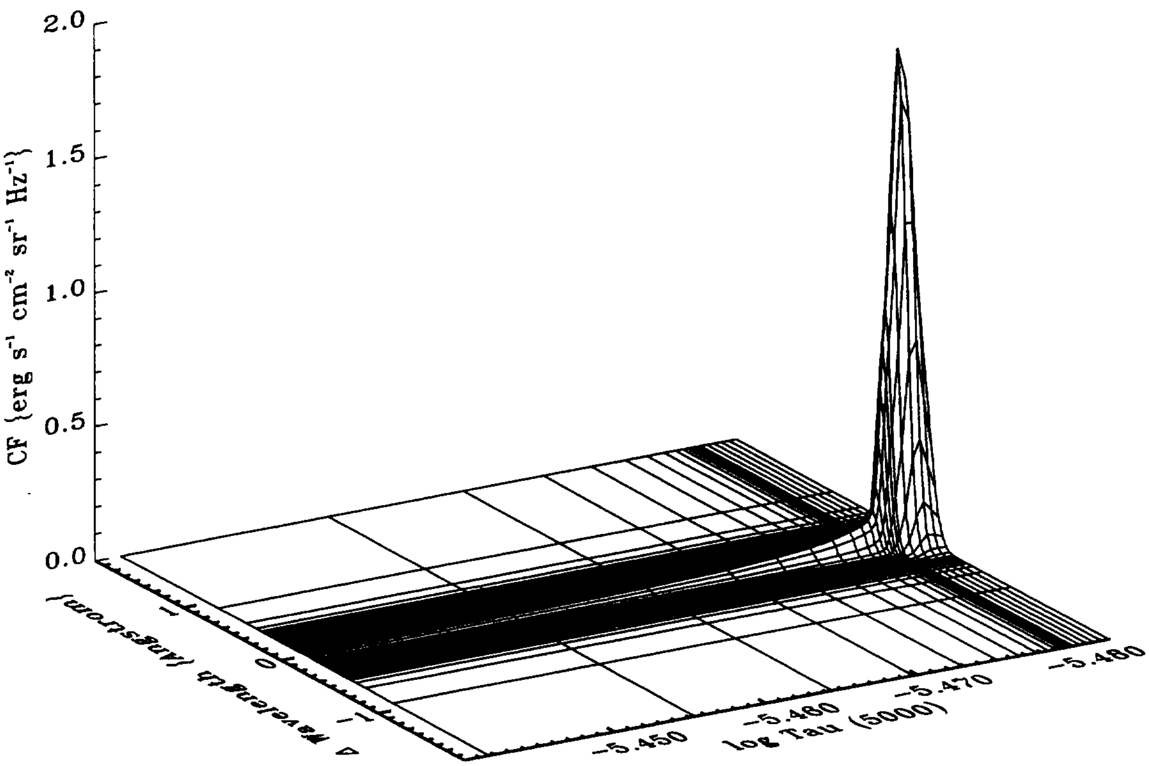

Figure 3: The contribution function of the He II λ 1640 transition, which illustrates the formation regions of the emergent emission line in the solar spectrum. The same portion of the solar atmosphere is depicted, but with log τ_{5000} as a height axis. The model is also the FAL Cm solar model. The deep "tail" due to coronal photoionization contributes only about 10% to the emergent emission line, but photoionization continues to be important for this transition at the base of the transition region.

4. Invited Talks

The PI was invited to present a talk on the formation of the solar helium spectrum at GSFC on May 5, 1994, in which he described the results from our recent non-LTE calculations of helium with the set of new solar atmosphere models incorporating particle diffusion and self-consistent transition regions. The Co-I presented an invited talk on the formation of the solar helium spectrum at the annual meeting of the Canadian Astronomical Society in May, 1994.

References:

Avrett, E. H., Fontenla, J. M., & Loeser, R. 1992, in *Infrared Solar Physics*, IAU Symp. 154, eds. D.M.Rabin, J.T.Jefferies, & C.Lindsey, p. 35

Brekke, P.O.L. 1992, Ph.D. Thesis, University of Oslo.

Fontenla, J.M., Avrett, E.H., & Loeser, R. 1993, ApJ, 406, 319.

Kisielius, R., Berrington, K.A., & Norrington, P.H. 1996, A&A, in press.

Sasselov, D.D., & Lester, J.B. 1994, ApJ, 423, 785.

Thomas, R. J., Neupert, W. M., & Thompson, W. T. 1991, *Bull.A.A.S.* 24, 1387.

Tobiska, W. K. 1991, J. Atmos. Terr. Phys. 53, 1005.

Wahlstrom, C. 1992, M.Sc. Thesis, University of Oslo.

Wahlstrom, C., & Carlsson, M. 1995, ApJ, 433, 417.